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Torsional system dynamics of low speed diesel engines based on instantaneous torque: Application to engine diagnosis

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ABSTRACT

Low speed large engines such as those found in marine applications or power plants present large and flexible crankshafts. These elements as well as all the others linked to them, such as the pistons, connecting rods, camshaft and the flywheel, form a torsional system of nonlinear nature for which it is very worthwhile to identify and solve relevant anomalies such as efficiency losses, power imbalance or injection system malfunctions. This work presents a torsional nonlinear model of a two-stroke low speed diesel engine that has been developed and validated through experiments, using the instantaneous torque (IT) between the generator and engine as the validation magnitude. The analysed system loads covered the whole operational range of the system, i.e. 55%, 70%, 85% and 100% of the engine's attainable power. The lumped torsional system was modelled with 16 degrees of freedom and was solved applying Fourier series expansion for the linear part of the system and with an iterative procedure for the nonlinear character of the system dynamics, which requires up to 12 iterations. A parameter model identification process was performed in Section 4 due to the uncertainty between the data supplied by the manufacturer and real data. As a result, the maximum error between the model and experimental data was reduced to 1.5%. In Section 5 a parametric study was developed that made it possible to establish the relationship between the in-cylinder combustion process and IT. This knowledge is taken into account in Section 6 to generate a proper set of inputs and outputs which is used to train an artificial neural network (ANN). Once trained, this network simulates the indicated mean power (WMI) at each cylinder with an error less than 1% for any load and engine condition. The main goal of the work is to develop a diagnostic tool for the identification and quantification of combustion-related anomalies that can contribute to maintaining the system efficiency as new.

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1. Introduction

Reciprocating systems, such as the diesel engine analysed in this work, are subjected to faults and malfunction which could be related to torsional vibrations derived from imbalance of cylinders. By means of the WMI of each cylinder, this paper proposes a useful tool to detect, locate and evaluate the differences between the combustion processes of cylinders. Similar to this methodology, [1] presents an indicated mean effective pressure estimation model and a torque balance control algorithm. Using both tools, the indicated mean effective pressure variation of each cylinder can be deduced. Also in this

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sense, [2] considers coupling between torsional vibrations and speed control in order to prevent malfunctions of a diesel engine.

The torsional system presented is formed by the crankshaft, pistons, connecting rods, chain-geared camshaft and flywheel coupled to an electric generator. This was modelled as a 16 degrees of freedom (16-DOF) lumped-mass system and it was characterised through inertia, stiffness and damping of the integrating elements. In order to validate the model, experimental data from an IT system based on strain gauge deformation were collected and processed. The model allows us to identify the real mechanical parameters of the system, showing relevant differences with the values supplied by the manufacturer.

The study performed highlighted the nonlinear nature of the dynamic system considered; an estimation of the torsional system by a linear model shows absolutely non-valid results and therefore a proper model has to take into account such behaviour.

Because of this, nonlinearity due to the dependence of the excitations on the crank angle and the torsional distortion of the system was analysed and solved through an iterative process based on Fourier series.

Finally, an ANN was configured and trained in order to obtain an estimation of the WMI at each cylinder as output from an input set integrated by IT Fourier coefficients. Such input–output sets were determined by modulating the pressure curves analytically in terms of the combustion process. This case study is presented and analysed.

2. Experimental data

Fig. 1 shows the system layout where the instantaneous angular speed (IAS) and IT are measured; the latter, which is based on strain gauges installed on the shaft between the engine and generator, has advantages over the first one from the point of view of engine diagnosis, as exposed in [3]. First of all, it provides absolute value of the mechanical torque, making this signal more appropriated for diagnosis purposes. On the other hand, IAS signal requires post-processing, higher acquisition rate, i.e. MHz versus kHz and a high-precision ferromagnetic pole band. Finally, IT has a low noise to signal ratio and its response is linear with the engine load. Works as in [4], where the burned fuel mass fraction is estimated from combustion torque and [5], where pressure curve parameters are determined from torque measurements highlight the importance of IS in engine diagnosis.

The measurements were done at different system loads of 55%, 70%, 85% and 100%, with a record length equivalent to the time required for a complete system cycle at the acquisition frequency of 100 kHz. The system operates at a constant angular speed of 125 rpm. A complete cycle covers a 360° crank angle, which means 48,000 points per signal, gathering 100 records for each signal and load condition.

The torque was measured through the relationship between shear stress and normal stress for pure torsion [6] with strain gauges oriented 45° to the shaft axis, where principal stresses are the maximum and shear is null:

$$\varepsilon = \frac{T}{\pi G R_C^3} \tag{1}$$

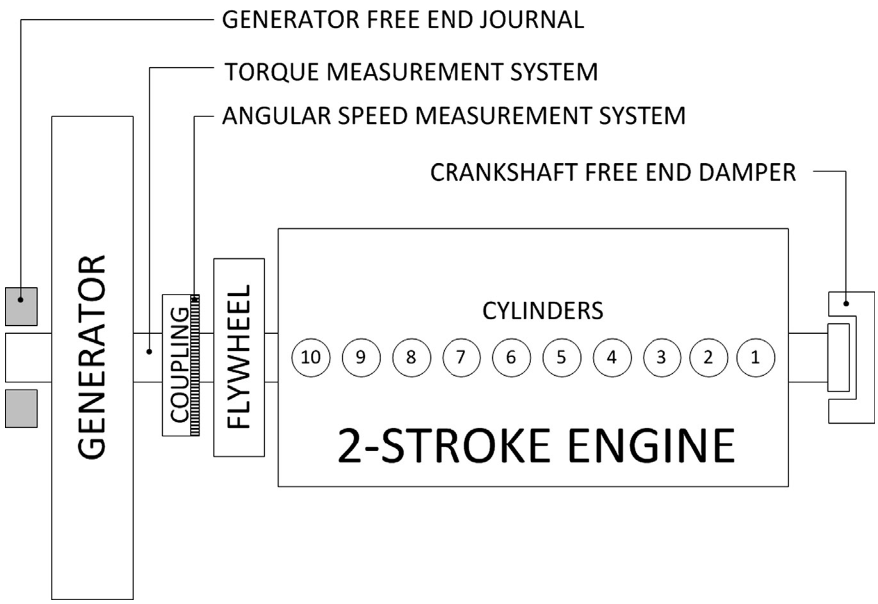

Fig. 1. Engine + generator system scheme and measurement elements.

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